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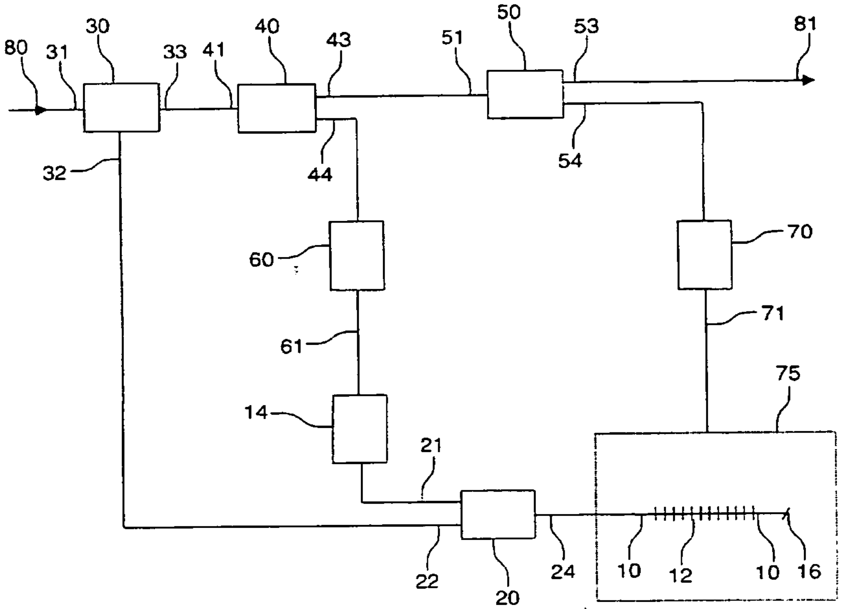
(54) **DISPOSITIF DE COMPENSATION DE DISPERSION DE RESEAU DE FIBRE REGLABLE**

(54) **TUNABLE FIBRE GRATING DISPERSION COMPENSATION DEVICE**



(57) It is known that the deleterious effects of chromatic dispersion in an optical communications system can be overcome by reflecting the optical signal from a chirped Bragg grating. In this invention, the dispersive characteristics of the Bragg grating may be altered by inducing a temperature gradient along the axis of the grating, where this gradient arises due to the absorption of photons from a pump source, and the subsequent emission of phonons. The central wavelength of the Bragg grating may be altered by stretching or compressing the grating, or by varying the ambient temperature surrounding the grating. The device has additional applications in compensation of polarization-mode dispersion, pulse shaping, and pre-chirping of directly modulated lasers.

ABSTRACT

It is known that the deleterious effects of chromatic dispersion in an optical communications system can be overcome by reflecting the optical signal from a chirped Bragg grating. In this invention, the dispersive characteristics of the Bragg grating may be altered by inducing a temperature gradient along the axis of the grating, where this gradient arises due to the absorption of photons from a pump source, and the subsequent emission of phonons. The central wavelength of the Bragg grating may be altered by stretching or compressing the grating, or by varying the ambient temperature surrounding the grating. The device has additional applications in compensation of polarization-mode dispersion, pulse shaping, and pre-chirping of directly modulated lasers.

SPECIFICATION

BACKGROUND – FIELD OF INVENTION

The present invention is related to the field of optical signal waveform manipulation in the time domain and, in particular, to devices containing an optical fibre grating capable of effecting wavelength-dependent delays.

BACKGROUND – DESCRIPTION OF PRIOR ART

A well-known phenomenon observed in optical materials is chromatic dispersion, in which the index of refraction of the material is dependent on the wavelength of an optical wave. As the velocity of light in a medium is dependent on the index of refraction, chromatic dispersion can cause optical waves of different wavelengths to travel at different speeds.

Chromatic dispersion is most commonly expressed as a change in propagation time through a distance of the optical material, with respect to a change in wavelength. For conventional single-mode (SM) optical fibres such as those used for optical telecommunications, the dispersion is approximately 17 ps/nm/km at a wavelength of 1550 nm.

Chromatic dispersion presents an obstacle to increasing system data rates and transmission distances. Optical pulses that are used to represent a stream of data contain a spread of wavelengths. The spread of velocities across the pulse spectrum causes the pulse to broaden in time as it traverses the fibre. Two adjacent pulses in a pulse train may thus overlap with each other due to this pulse broadening. This overlap, known as “intersymbol interference,” can cause errors in the received data. In analog systems, chromatic dispersion leads to distortion of the received signal.

The prior art proposes several methods by which the deleterious effects of chromatic dispersion can be minimized. A significant reduction of dispersive effects can be achieved by transmitting data at a wavelength at or near a zero-dispersion wavelength of the fibre. In standard SM fibre, this occurs near 1.3 μm. However, such a solution limits the maximum distance between amplifiers or repeaters, as the attenuation coefficient of silica fibre is greater at 1.3 μm than at 1550 nm.

The effects of chromatic dispersion can be remedied in the electronic domain by inserting detectors into the link at distances short enough that individual bits of data can still be distinguished with low probability of error. The signal is then re-transmitted with narrow pulse widths by another laser source. Such a scheme adds undue complexity to the link.

A third approach is to compensate for accumulated pulse broadening by introducing into the optical link a short section of dispersion-compensating fibre (DCF). Typically, DCF exhibits chromatic dispersion substantially greater in magnitude, and opposite in sign, to that of standard fibre. The broadened optical pulse is compressed into its original shape upon traversing the DCF. An example of chromatic dispersion compensation is provided by Nuyts et al, in "Performance improvement of 10 Gb/s standard fiber transmission systems by using SPM effect in the dispersion compensated fiber," IEEE Photonics Technology Letters 8 (10):1406-1408 (1996). This approach suffers from increased attenuation due to the added fibre and associated splices. In addition, it is difficult to design a DCF whose dispersion is a constant multiple of that of standard fibre across the entire transmission spectrum used for wavelength-division multiplexed communication schemes.

Yet another approach to compensating for chromatic dispersion utilizes a linearly chirped fibre Bragg grating (FBG). The grating consists of a perturbation in the refractive index of an optical fibre. Each spectral component of an input

optical signal is reflected from a position in the grating where the perturbation is phase-matched to the optical wavelength. Wavelengths that are required to experience a greater time delay upon passing through the device are allowed to penetrate deeper into the FBG through an appropriate design of the phase-matching condition (referred to as "chirp"). Such a device has been analyzed in systems experiments by several authors, such as Loh et al, in "10 Gb/s transmission over 700 km of standard single-mode fiber with 10-cm chirped fiber grating compensator and duobinary transmitter," IEEE Photonics Technology Letters 8 (9):1258-1260 (1996).

All of the dispersion compensation schemes detailed above suffer from the fact that they do not allow the user to tune the magnitude of applied dispersion. In dynamically reconfigurable networks, or in systems that operate via optical packet switching, various signals incident upon the dispersion compensator may have originated from vastly different locations, and thus the accumulated dispersion among bit packets may vary. In addition, transmitter sources may degrade over time, or be upgraded, altering the spectrum of the optical signals. It is clear that the utility of the Bragg grating as a dispersion compensator can be improved by allowing for dynamic tuning of the chirp magnitude and central wavelength, in response to the compensation requirements of the input signal.

Several authors have suggested means by which the dispersion of an FBG can be tuned. It has long been established that the phase-matching conditions within an FBG are dependent upon the local axial strain. One method of applying an axially varying strain involves bonding the grating to a magnetostrictive rod, which is subjected to a magnetic field (Cruz et al, "Fibre Bragg gratings tuned and chirped using magnetic fields," Electronics Letters 33 (3):235-236 (1997)). Although it is possible to tailor an axially varying strain profile through the use of several magnets of varying strength and polarity, this

design suffers from a highly nonlinear relationship between dispersion and field strength due to the magnetic saturation of the rod.

A further method by which axial strain gradients can be applied to an optical fibre involves bonding the fibre to a flexible cantilevered beam. When the free end of the beam is displaced or torqued, the strain experienced by the beam is coupled to the fibre. Such a device is reported by Imai et al, "Dispersion Tuning of a Linearly Chirped Fiber Bragg Grating Without a Center Wavelength Shift by Applying a Strain Gradient," IEEE Photonics Technology Letters 10 (6):845-847 (1998). This solution requires several moving parts, which add to the cost of the device while potentially limiting its lifetime.

Piezoelectric stretchers have also been used to apply axial strain. Ohn et al report of the achievement of an axial strain gradient through the use of a stack of piezoelectric elements, each under the influence of a different voltage - see "Dispersion variable fibre Bragg grating using a piezoelectric stack," Electronics Letters 32 (21):2000-2001 (1996). Another design uses a simpler single piezoelectric element to stretch a nonlinearly chirped grating (Willner et al, "Tunable Compensation of Channel Degrading Effects Using Nonlinearly Chirped Passive Fiber Bragg Gratings," IEEE Journal of Selected Topics in Quantum Electronics 5 (5):1298-1311 (1999), and Feng et al, United States Patent #5,982,963 (Nov. 9, 1999). The tuning speed of these devices is limited by the stretcher to below 500 Hz. In addition, they require a high-voltage (zero to 500 V) source, which may be undesirable in remote locations or in the vicinity of high-sensitivity electronics. Furthermore, dynamic straining can accelerate the degradation of a grating.

A temperature gradient along the grating axis will also provide the necessary tunable chirp. A recent proposal by Eggleton et al ("Dual on-fiber thin film heaters for fiber gratings with independently adjustable central wavelength and chirp," in *Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides,*

OSA Technical Digest (Optical Society of America, Washington DC, 1999), pp. 6-8) suggests that such a gradient can be attained by passing an electrical current through resistive gold films deposited on the grating surface. Chirp and wavelength are tuned independently through a constant-thickness and tapered film, respectively. This method requires a large number of fabrication steps, including electron beam evaporation of titanium and gold layers onto the fibre surface, wire bonding for electrical contacts, plasma vapour deposition of an insulating silicon dioxide layer, and finally a second deposition of gold that requires careful control of the thickness gradient along the fibre axis.

OBJECT AND ADVANTAGES

Accordingly, the object of the present invention is to provide a means by which the chirp characteristics and central wavelength of a fibre Bragg grating may be tuned.

The invention shows distinct advantages over the prior art. With proper design, optical signals of any practical wavelength can be used, allowing for operation of the device within the low – attenuation region of the optical spectrum around 1550 nm. It is possible to dynamically tune the dispersion and center wavelength of the invention independently, in order to recover various input signals that have suffered chromatic dispersion upon travelling through optical links with differing characteristics. Furthermore, the present invention does not require complicated fabrication procedures, as does the thin-film heater device discussed in the prior art.

SUMMARY OF THE INVENTION

The present disclosure describes a fibre Bragg grating whose dispersive qualities can be dynamically varied in a controllable manner. The chirp of the grating may be altered by inducing a temperature gradient along the grating

length, where this gradient arises due to the absorption of photons from a pump source, and the subsequent emission of phonons. The central wavelength of the Bragg grating may be altered by stretching or compressing the grating, or by varying the ambient temperature surrounding the grating. Construction of the device is simple.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram illustrating a grating in a wave-guiding element.

FIG. 2 is a diagram illustrating the formation of Bragg gratings in optical fibre.

FIG. 3 is a diagram of the first embodiment of the dispersion compensation device, illustrating the pump-induced chirping of the grating.

FIG. 4 is a diagram of the second embodiment of the dispersion compensation device, illustrating the pump-induced chirping and strain-induced wavelength tuning of the grating.

FIG. 5 is a diagram of the third embodiment of the dispersion compensation device, illustrating the pump-induced chirping and ambient temperature-induced wavelength tuning of the grating.

FIG. 6 is a diagram of a chromatic dispersion detection and compensation system, using either of embodiments 2 or 3.

FIG. 7 is a diagram of a system to cancel direct modulation chirp of a laser

REFERENCE NUMERALS IN DRAWINGS

10	absorbing fibre	12	grating
14	pump	16	low-reflectivity termination

20	wavelength-division multiplexer	21	port of WDM
22	port of WDM	24	port of WDM
30	optical routing device	31	port of optical routing device
32	port of optical routing device	33	port of optical routing device
40	optical coupler	41	port of optical coupler
43	port of optical coupler	44	port of optical coupler
50	optical coupler	51	port of optical coupler
53	port of optical coupler	54	port of optical coupler
60	dispersion stabilization circuit	61	pump control signal
70	wavelength stabilization circuit	71	wavelength control signal
75	wavelength tuning mechanism	76	fibre straining mechanism
77	temperature-controlled chamber	80	input optical signal
81	output optical signal	85	laser
86	laser output	90	modulation signal
95	prechirp circuit	96	pump control signal
99	prechirped laser signal	101	input optical signal
102	output optical signal	111	λ_1
112	λ_2	113	λ_3
120	grating control	200	UV light source
210	phase mask	220	translating mirror

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates the means by which a fibre Bragg grating can effect wavelength-dependent time delays upon an optical signal. A fibre 10 contains a grating 12, that arises due to perturbations in the fibre's refractive index. The grating periods are shown as abrupt planes in FIG. 1, but may take any functional form. The period of the index fluctuations may be dependent upon position within the grating, and is indicated as $\Lambda(z)$. The refractive index, when averaged over a large number of periods, may also exhibit a dependence upon position in the grating, indicated as $n_o(z)$. Furthermore, the amplitude of the

index fluctuations may vary along the grating length. This is represented by $\Delta n(z)$. The refractive index profile along the grating is thus expressed as:

$$n(z) = n_o(z) + \Delta n(z) \cos\left(\frac{2\pi z}{\Lambda(z)} + \Phi_o\right),$$

where Φ_0 is the phase of the grating at z = 0.

An input optical signal 101 contains a spread of wavelengths. Each wavelength reflects from the position within the grating where the wavelength satisfies the Bragg phase-matching condition: $\lambda(z) = 2n(z)\Lambda(z)$. The individual reflections of representative wavelengths are indicated in FIG. 1 as λ_1 111, λ_2 112, and λ_3 113, where λ_3 113 experiences the longest delay, and λ_1 111 experiences the shortest delay. The reflections combine in an output optical signal 102.

Grating 12 can be adjusted to alter the relative delays of the wavelengths contained in input optical signal 101. A grating control 120 is implemented to vary at least one of n(z) and Λ(z) within grating 12.

An optional low-reflectivity termination 16 may be applied to the end of the fibre opposite the input end. This will reduce the ability of light whose wavelength does not fall within the operating region of grating 12 to couple into output optical signal 102. Low-reflectivity termination 16 may take the form of an angle-polished cleave, several tight fibre turns, or immersion into an index-matching fluid, for example.

FIG. 2 is a simplified diagram explaining how the permanent refractive index perturbation is introduced into the fibre. Absorbing fibre 10 is placed next to a phase mask 210. A narrow beam width ultraviolet (UV) light source 200, such as an excimer laser, is scanned along the phase mask using a translating mirror 220. Interference between the +1st and -1st order diffracted beams forms a quasi-periodic intensity distribution of UV light along the length of absorbing fibre

10. Absorption of the UV light within absorbing fibre 10 creates localized changes in the refractive index. To increase the amplitude of the refractive index modulation, a greater quantity of UV energy is made incident upon absorbing fibre 10. This is known as the "writing" process.

As the refractive index change due to UV light absorption is positive, forming the perturbation in this manner may result in an undesired $n_o(z)$ profile. This can be rectified by removing phase mask 210 and scanning UV light source 200 along absorbing fibre 10 once more, varying the fluence at each location so as to achieve the desired $n_o(z)$ profile. This procedure is known as "trimming."

FIG. 3 shows the first embodiment of the dispersion compensation device. A pump source 14 is coupled into absorbing fibre 10 through a wavelength division multiplexer (WDM) 20. The pump photons are rapidly absorbed within absorbing fibre 10, and a portion of the absorbed energy is re-emitted as phonons (lattice vibrations of the host material). The lattice vibrations produce a localized heating of absorbing fibre 10. In the case where the waveguide dimension perpendicular to the flow of pump photons is very small in comparison to the waveguide dimension parallel to the flow of pump photons, heat transfer in the waveguide will occur primarily in the perpendicular direction. This will ensure that the temperature profile in the parallel direction has the same functional form as the absorption profile of the pump photons. This criterion is met in optical fibre.

The Bragg phase-matching condition is dependent upon the local temperature at each position in grating 12. It can be expressed as $\lambda(z,T) = 2n(z,T)\Lambda(z,T)$, where T is the local temperature. The temperature dependence of refractive index n arises due to the thermo-optic effect, while the temperature dependence of the grating period Λ arises due to the thermal expansion of the host material. By way of example, for a grating written in SM silica fibre, the temperature coefficient of Bragg wavelength is approximately 14 pm / °C at a

wavelength of 1550 nm, due primarily to the thermo-optic effect (Othonos et al, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing, Boston: Artech House, 1999).

The speed with which the dispersive properties of grating 12 can be varied (the "dispersion modulation bandwidth," "DMB") is highly dependent upon the fibre geometry and the dopant species. In general, the DMB is dictated by the slowest of a number of time constants, including:

1) the time required for the pump photons to traverse grating 12,
2) the sum of all energy transition lifetimes within the dopant species, up to and including the lifetime(s) of the non-radiative transition(s) that produce the majority of the temperature increase,
3) the time required for the temperature profile generated within the doped region of absorbing fibre 10 to stabilize across a cross-sectional area equal to the mode field area of the input optical signal 80 within absorbing fibre 10,
4) the time required for the temperature within absorbing fibre 10 to relax to the ambient temperature when pump 14 is turned off.

In the case of an optical fibre with rare-earth dopants such as erbium/ytterbium or thulium/holmium, the DMB is roughly 1 kHz, dictated by factors 2) and 4) above. Factors 1) and 3) are negligible for most geometries and dopant species.

An input optical signal 80 is coupled into absorbing fibre 10 through WDM 20. A reflected and time-delayed output optical signal 81 is coupled out of absorbing fibre 10 through WDM 20.

The preferred method of joining optical fibres used in FIG. 3 and all subsequent figures is fusion splicing. Mechanical splicing or free-space coupling may also be used, at the expense of greater insertion loss.

FIG. 4 shows the second embodiment of the dispersion compensation device. It is similar to FIG. 3, but also includes a fibre straining mechanism 76, which applies tensile or compressive strain along the axis of the absorbing fibre in order to tune the central wavelength of grating 12. Fibre straining mechanism 76 may be one of several devices known in the prior art, including a cantilevered beam, piezoelectric element, or magnetostrictive element. It is essential that the inclusion of fibre straining mechanism 76 does not significantly influence the heat transfer properties of absorbing fibre 10.

The Bragg phase-matching condition is dependent upon the local strain at each position in grating 12. It can be expressed as $\lambda(z,\varepsilon) = 2n(z, \varepsilon)\Lambda(z, \varepsilon)$, where ε is the local strain. The strain dependence of refractive index n arises due to the elasto-optic effect, while the strain dependence of the grating period Λ arises due to the lengthening of grating 12. By way of example, for a grating written in SM silica fibre, the strain coefficient of wavelength is approximately 1.2 pm / $\mu\varepsilon$. (*Ibid.*).

FIG. 5 shows the third embodiment of the dispersion compensation device. It is similar to FIG. 3, but also includes a temperature-controlled chamber 77, into which grating 12 is placed. Temperature-controlled chamber 77 is used to vary the ambient temperature surrounding grating 12, which shifts the central wavelength according to the formulae provided in the description of FIG. 3. It is important that the inclusion of temperature-controlled chamber 77 does not significantly influence the heat transfer properties of absorbing fibre 10.

FIG. 6 illustrates the use of the invention as a compensator for chromatic dispersion in accordance with the second or third embodiment of the invention. Grating 12, WDM 20, and pump 14 are assembled as in FIG. 3, and operate as outlined in that figure.

Component 20 is a wavelength-division multiplexer, characterized by the following relevant optical flow paths: light having a wavelength similar to that of the optical input signal and entering port 22 exits via port 24. Light having a wavelength similar to that of the optical input signal and entering port 24 exits via port 22. Light having a wavelength similar to that of the pump and entering port 21 exits via port 24.

Component 30 is an optical routing device, characterized by the following optical flow paths: light entering the device via port 31 exits the device via port 32. Light entering the device via port 32 exits the device via port 33. This device may take the form of an optical circulator or a 3 dB coupler, for example.

Component 40 is an optical coupler. Of light entering optical coupler 40 through port 41, a small percentage exits via port 44, and the remaining portion exits via port 43.

Component 50 is also an optical coupler. Of light entering optical coupler 50 through port 51, a small percentage exits via port 54, and the remaining portion exits via port 53.

Component 60 represents a dispersion stabilization circuit, consisting of a dispersion measurement system and pump drive electronics. The required grating chirp is detected using the signal exiting port 44 of the first optical coupler, and is converted into a pump control signal 61.

Component 70 represents a wavelength stabilization circuit, consisting of a wavelength measurement system and wavelength tuning electronics. The required wavelength tuning is detected using the signal exiting port 54 of the second optical coupler, and is converted into a wavelength control signal 71.

An optical input signal 80 enters optical routing device 30 and is routed to grating 12 through WDM 20. The signal reflected from grating 12 returns to optical routing device 30 by the same path. A portion of the signal is coupled out of the transmission line by optical coupler 40, and is used to maintain the desired chirp characteristics of grating 12 by causing dispersion stabilization circuit 60 to maintain an appropriate control signal 61 to pump 14. A second portion of the signal is coupled out of the transmission line by optical coupler 50, and is used to maintain the correct central wavelength of grating 12 by causing wavelength stabilization circuit 70 to deliver an appropriate control signal 71 to wavelength tuning mechanism 75.

FIG. 7 illustrates the use of the invention as chirp compensator for directly modulated lasers in accordance with the second or third embodiment of the invention. Grating 12, WDM 20, and pump 14 are assembled as in FIG. 3, and operate as outlined in that figure.

A laser 85 is directly modulated using a modulation signal 90. The optical spectrum of an output 86 of a laser 85 is chirped due to the direct modulation, and it is desirable to reduce this chirp before the signal is transmitted through an optical link. Laser output 86 is routed to grating 12 through optical routing device 30 and WDM 20, as outlined in the description of FIG. 5. Modulation signal 90 is detected by a prechirp circuit 95, which calculates the effect of modulation signal 90 on laser output 86. Prechirp circuit 95 produces a pump control signal 96 that is used to control pump 14. The reflected laser signal is routed through WDM 20 and optical routing device 30 to form a prechirped laser signal 99.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

A first embodiment of the dispersion compensation device includes a segment of optical fibre into which a grating has been written. The fibre has been doped with one or more chemical species that exhibit strong absorption of

photons over a well-defined range of wavelengths, whereby a substantial portion of the energy from the absorbed photons is subsequently emitted into the host material in the form of phonons. The preferred selection of the absorptive dopant species consists of ions of the group of elements known as rare-earths. It is important that the optical fibre also be photosensitive, to facilitate writing of the grating. The optical signal for which dispersion is required ("the signal") is coupled into the grating. Also coupled into the grating is a source of photons of a wavelength corresponding to a region of strong absorption by the dopant species ("the pump").

The distribution of absorbed pump power along the fibre is dependent upon such factors as the incident pump power, dopant density and absorption cross-section. At low pump powers, the absorption approaches an exponentially decreasing profile, while at high pump powers, the absorption saturates, producing a constant value of absorbed power along the grating. In the intermediate pumping range, it is possible for the absorption profile to provide a fairly linear chirp distribution for a range of pump powers. Linearity can be enhanced by applying an appropriate pre-chirp profile $\Lambda(z)n_o(z)$ to the un-pumped grating during the writing and trimming processes.

The existence of a profound grating chirp within a pumped, highly-doped fibre was recently discussed by Xu et al, ("Pump-Induced Thermal Effects in Er-Yb Fiber Grating Lasers," IEEE Photonics Technology Letters 10 (9):1253-1255 (1998), and again by the same authors (Man et al, "Frequency Instability in Er/Yb Fiber Grating Lasers due to Heating by Nonradiative Transitions," IEEE Photonics Technology Letters 11 (11):1390-1392 (1999)). The authors were not concerned with using the grating as a dispersion compensator; rather, they concluded that thermal stabilization is necessary when designing highly doped fibre grating lasers.

Furthermore, a comprehensive study of the static and dynamic temperature profiles within pumped, doped fibres, not inclusive of a Bragg grating, has been published by Davis et al, ("Thermal Effects in Doped Fibers," Journal of Lightwave Technology 16 (6):1013-1023 (1998)). These authors were investigating the detrimental effects of thermal phase shifts on interferometer-based optical switches, and no applicability to dispersion compensation was mentioned. With reference to the aforementioned paper, It is worth mentioning that the principle of operation of the present invention (the thermo-optic effect) differs significantly from that utilized in doped fibre optical switches (a resonantly-enhanced nonlinear index shift). In the latter, the pump depletes the ground state of the dopant species, bleaching the absorption of photons at a corresponding signal wavelength. This leads to an index shift at the signal wavelength, via the Kramers-Krönig causality principle. Davis et al point out that when the dopant species is a triply-ionized rare-earth ion, the thermo-optic effect is more prominent than the resonantly-enhanced nonlinear index shift. In fact, this is irrelevant, as the present invention is designed such that dispersion compensation occurs over a range of wavelengths that does not fall within the absorption bandwidth of the dopant species.

The chirp bandwidth can be expressed as a function of the pump power, the pump absorption coefficient within the doped fibre, the $\Lambda(z)n_o(z)$ profile of the un-pumped grating, the grating length, the fibre's thermo-optic and thermal expansion coefficients, the fibre geometry and heat transfer properties, and the quantum efficiency of phonon emission for the dopant species in the host matrix.

As an example, consider silica fibre doped with trivalent erbium and ytterbium ions, with an absorption coefficient of 350 dB/m, or $\alpha = 80.59\ m^{-1}$. The pump wavelength is 980 nm, and the optical gain spectrum of the doped fibre is centered at 1550 nm. The product $\Lambda(z)n_o(z)$ is constant along a 5 cm grating length at zero pump power, and is chosen such that the center wavelength of the un-pumped device is $\lambda_B = 2\Lambda(z)n_o(z) = 1540$ nm. The pump power is $P_0 = 20$

mW, and it is assumed that this power is not sufficient to saturate the absorption. The power profile within the grating is thus:

$$P(z) \quad = \quad P_0 e^{-\alpha z}.$$

The quantum efficiency of phonon emission can be estimated as $\eta_{phonon} = 1 - \eta_{photon}$, where η_{photon} is the quantum efficiency of photon emission. As each pump photon produces one signal photon in the Er / Yb system, $\eta_{phonon} \approx 1-(980 / 1550) = 0.37$. The gradient in thermal power (i.e. the power that contributes to fibre heating) is thus:

$$\frac{dP_{thermal}}{dz} \quad = \quad \eta_{phonon} \alpha P_0 e^{-\alpha z}.$$

The temperature rise (above the ambient temperature) due to this power gradient can be derived using the previous reference and Rao et al, "In-Fiber Bragg-Grating Temperature Sensor System for Medical Applications," Journal of Lightwave Technology 15 (5):779-785 (1997):

$$\Delta T \quad = \quad \frac{1}{2\pi} \frac{dP_{thermal}}{dz} \left[\frac{\ln\left(r_1 / r_0 \right)}{k} + \frac{1}{\gamma r_1} \right],$$

where r_1 and r_0 are the radii of the fibre cladding and core, k is the thermal conductivity, and γ is a heat transfer coefficient between the fibre surface and its surroundings.

The temperature change is easily transformed into a Bragg wavelength shift using the equation: $\Delta\lambda_B = \lambda_B (\beta + \sigma) \Delta T$, where β and σ are the thermal expansion and thermo-optic coefficients.

Combining the above equations, the Bragg wavelength shift as a function of position within the grating can be found:

$$\Delta\lambda_B(z) \quad = \quad \frac{\eta_{phonon} \alpha P_0 \lambda_B}{2\pi} (\beta + \sigma) \left[\frac{\ln\left(r_1 / r_0 \right)}{k} + \frac{1}{\gamma r_1} \right] e^{-\alpha z}$$

Using r_1 = 62.5 μm, r_0 = 2.33 μm, silica properties k = 1.38 W / (m.K), γ = 100 W / (m^2.K), $\beta = 0.55 \times 10^{-6}\ K^{-1}$ and $\sigma = 8.6 \times 10^{-6}\ K^{-1}$, the Bragg wavelength shift due to pumping is $\Delta\lambda_B(z) = (4.1 \times 10^{-10})\ e^{-\alpha z}$. Over a 5 cm grating, the chirp bandwidth of the pumped grating is 0.2 nm.

By examining the Bragg wavelength shifts at both ends of the grating, the center wavelength of the pumped grating can be calculated:

$$\lambda_{B.pumped} = \lambda_{B.un-pumped} + \frac{\eta_{phonon}\alpha P_0 \lambda_B}{4\pi}(\beta+\sigma)\left[\frac{\ln\left(r_1/r_0\right)}{k}+\frac{1}{\gamma r_1}\right](1-e^{-\alpha L}),$$

where $\lambda_{B,\ un\text{-}pumped}$ is the center wavelength of the grating at zero pump power, and L is the grating length.

In the preceding example, the emission wavelength of the dopant ions (1550 nm) was similar to the center wavelength of the grating (1540 nm). It must be noted that when the grating bandwidth overlaps with the gain bandwidth of the pumped fibre, there is the possibility that the device will lase in a distributed feedback manner at high pump powers. In addition, unwanted optical gain, loss, or noise may be present in the compensated signal. This being the case, it is advisable that in selecting a suitable doped fibre, one be chosen that does not exhibit optical gain in the range of wavelengths for which dispersion compensation is required.

A preferred implementation of the means by which the pump and the signal are coupled into the grating consists of a fused-fibre wavelength division multiplexer. Other implementations take the form of a bulk-optic WDM, dichromic filter based WDM, or planar waveguide WDM.

A second embodiment of the dispersion compensation device includes a grating with tunable dispersion through the pump absorption process described previously, where the grating may be stretched or compressed concurrently with the application of the temperature gradient. In this manner, the dispersion and the center wavelength may be tuned simultaneously.

In one implementation of this second embodiment, the dispersion and center wavelength are independent of one another with respect to the aforementioned tuning methods.

In another implementation of this second embodiment, the dispersion and center wavelength are dependent upon one another with respect to the aforementioned tuning methods.

One implementation of the stretching or compressing element of this second embodiment uses a magnetostrictive element to strain the grating according to an external control signal.

Another implementation of the stretching or compressing element of this second embodiment uses a piezoelectric element to strain the grating according to an external control signal.

Another implementation of the stretching or compressing element of this second embodiment uses a cantilevered beam to strain the grating according to an external control signal.

A third embodiment of the dispersion compensation device includes a grating with tunable dispersion through the pump absorption process described previously, where the grating may be subjected to a controllable variation of the ambient temperature. In this manner, the dispersion and central wavelength may be tuned simultaneously.

While the primary use of the invention is to provide dispersion cancellation in an optical network, it is realized that there are several other functions for the invention. One such function is chirp cancellation in directly modulated lasers. The tunability of the grating's chirp allows the modulation signal to drive the grating such that a complementary chirp is applied to effect a chirp cancellation. Another function of the invention is as a dispersive element for the formation of stable output pulses in a mode-locked laser, while a further function of the invention is as a tunable compensator for polarization mode dispersion.

CONCLUSION, RAMIFICATIONS, AND SCOPE

In summary, the present invention discloses a fibre Bragg grating with means to tune the chirp and center wavelength. The chirp is tuned by inducing a temperature gradient within the grating, where this gradient arises due to absorption of photons from a pump source, and subsequent emission of phonons into the host matrix. The device is easily constructed, and can tune the chirp magnitude at a rate of approximately 1 kHz. In light of the immediate and future requirements of optical communications systems to tune the dispersion within a transmission link, it is believed that devices of this design represent the basis for notable improvements in such systems.

While the invention has been described above with reference to specific embodiments, it is anticipated that various modifications, alternate constructions, and equivalents will be obvious to those with skill in the art. For instance, the fibre Bragg grating may be replaced by a planar waveguide grating. Also, modifications to the reflectivity and dispersion spectra can be exacted through apodization of the grating. Thus, it is to be understood that the above description is intended merely to illustrate the invention and not to limit the scope of the invention as defined in the appended claims.

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CLAIMS

We claim:

1. An optical device, comprising:

a wave-guiding element having an optical axis along which optical energy may be transported and having an effective refractive index along said optical axis, and

a region in said wave-guiding element containing a perturbation of said refractive index, where said perturbation has a well-defined spatial period along said optical axis, and

a region in said wave-guiding element coincident with said perturbation containing one or a plurality of chemical dopant species, and

a source of photons of a wavelength that exhibits significant absorption within said chemical dopant species,

wherein a product of said effective refractive index and said spatial period is a function of position along said optical axis to effect a phase-matching condition such that the reflection of an optical wavelength from said perturbation has a dependence on a position along said optical axis, and

wherein a substantial portion of optical energy absorbed by said chemical dopant species is emitted in the form of phonons.

2. A device as in claim 1, wherein the temperature of said wave-guiding element is a function of position along said optical axis.

3. A device as in claim 2, wherein said temperature of said wave-guiding region is a function of a magnitude of optical power absorbed by said chemical dopant species along said optical axis.

4. A device as in claim 2, wherein said effective refractive index and said spatial period are functions of said temperature, whereby said phase-matching condition may be controlled by said source of photons.

5. A device as in claim 4, wherein the variation of said effective refractive index along said optical axis is chosen so as to produce a predetermined variation of said effective refractive index along said optical axis, corresponding to a similarly predetermined temperature along said optical axis.

6. A device as in claim 1, wherein said wave-guiding element includes an optical fibre.

7. A device as in claim 1, wherein said wave-guiding element includes a planar waveguide.

8. A device as in claim 1, wherein said source of photons is introduced into said wave-guiding element coincident with an input optical signal by a wavelength-selective coupling device.

9. A device as in claim 8, wherein said wavelength-selective coupling device includes a fused-fibre wavelength-division multiplexer.

10. A device as in claim 8, wherein said wavelength-selective coupling device includes a bulk-optic wavelength-division multiplexer.

11. A device as in claim 8, wherein said wavelength-selective coupling device includes a dichromic filter wavelength division multiplexer.

12. A device as in claim 8, wherein said wavelength-selective coupling device includes a planar waveguide wavelength-division multiplexer.

13. A device as in claim 1, further comprising a transducer engaged to said wave-guiding element, said transducer operating to apply a mechanical strain along said optical axis of said wave-guiding element.

14. A device as in claim 13, wherein said transducer includes one or a plurality of piezoelectric elements, said piezoelectric elements operating in response to one or a plurality of control voltages.

15. A device as in claim 13, wherein said transducer includes one or a plurality of magnetostrictive elements, said magnetostrictive elements operating in response to one or a plurality of control magnetic fields.

16. A device as in claim 13, wherein said transducer includes one or a plurality of cantilevered beams, said cantilevered beams operating in response to one or a plurality of control forces.

17. A device as in claim 1, further comprising a temperature-controlled chamber surrounding said wave-guiding element, said temperature-controlled chamber operating to change the ambient temperature surrounding said wave-guiding element, and said temperature-controlled chamber operating in response to a control electrical signal.

18. A device as in claim 1, wherein the amplitude of said perturbations is a function of position along the grating.

FIG. 1

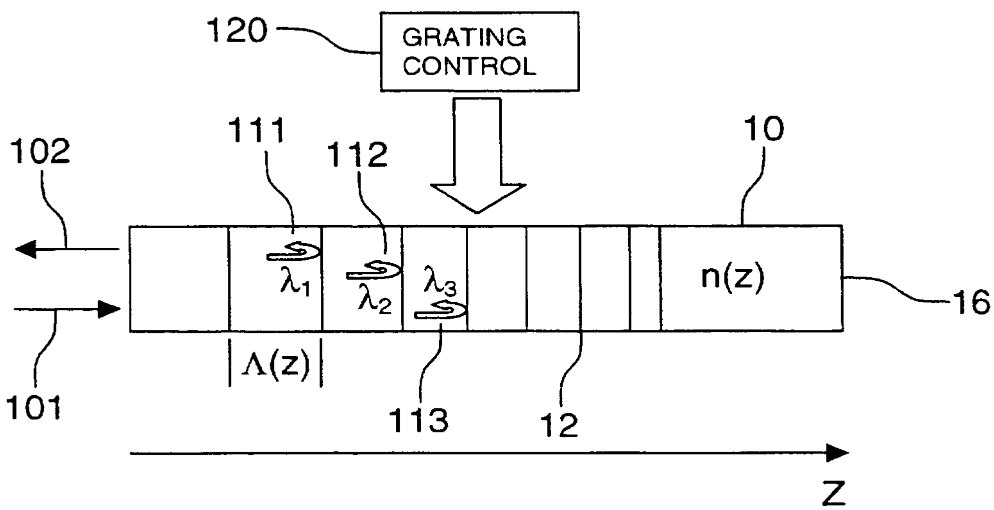

FIG. 2

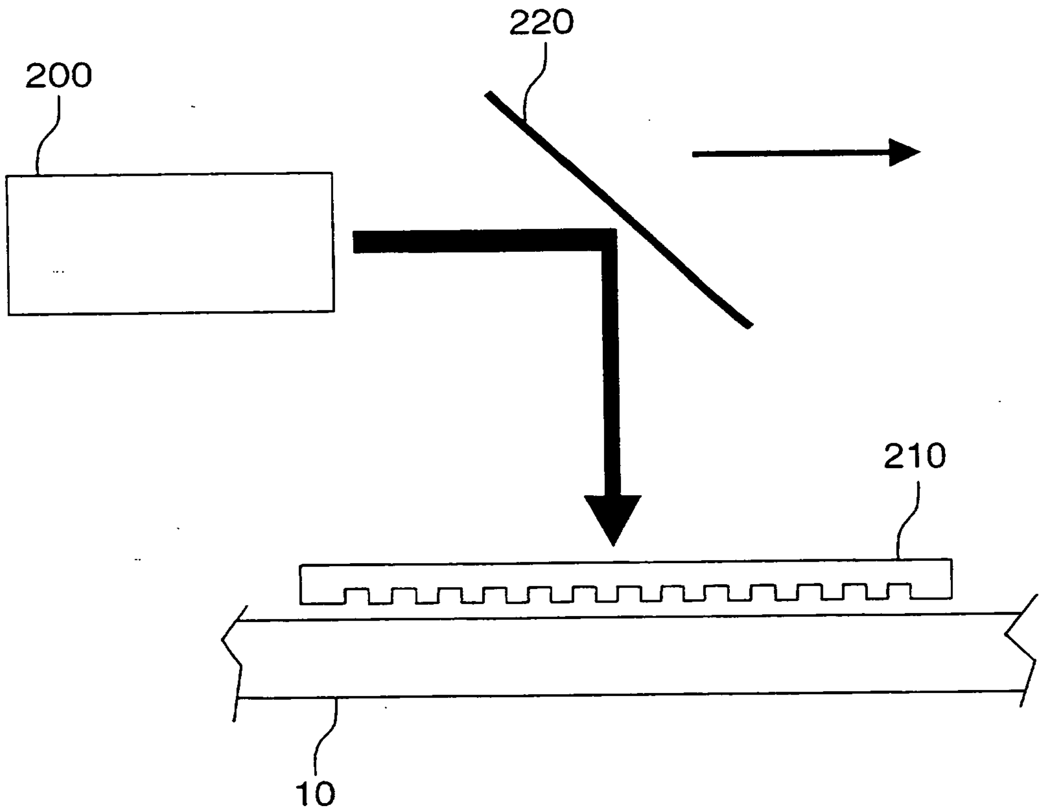

FIG. 3

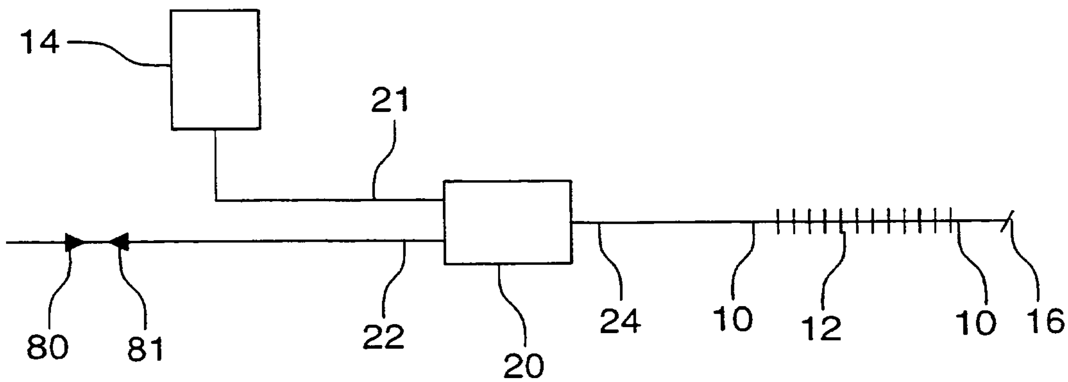

FIG. 4

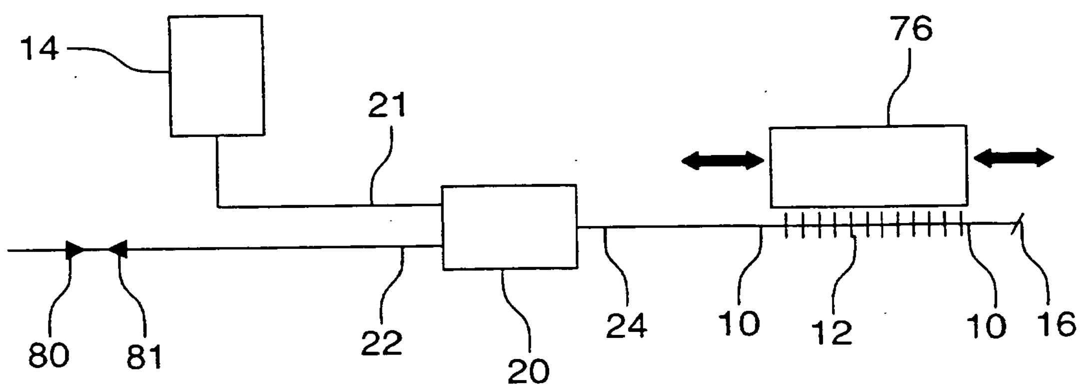

FIG. 5

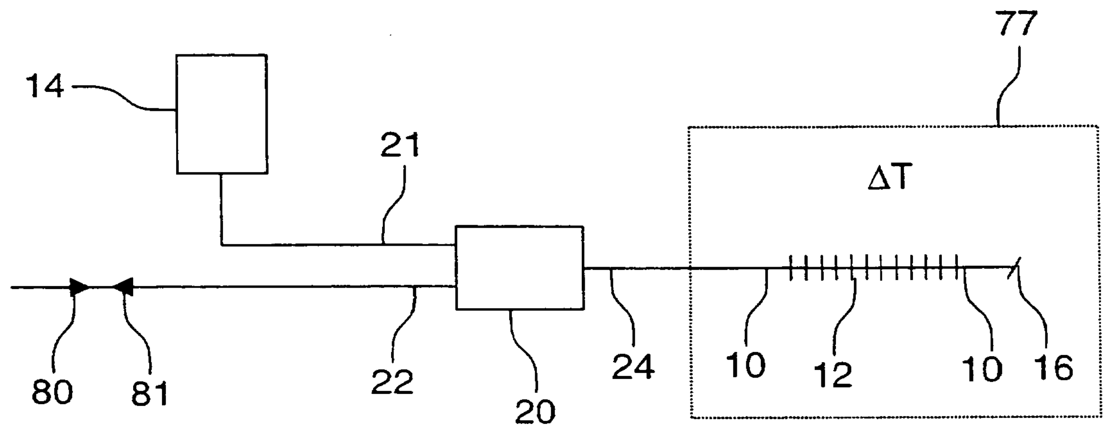

FIG. 6

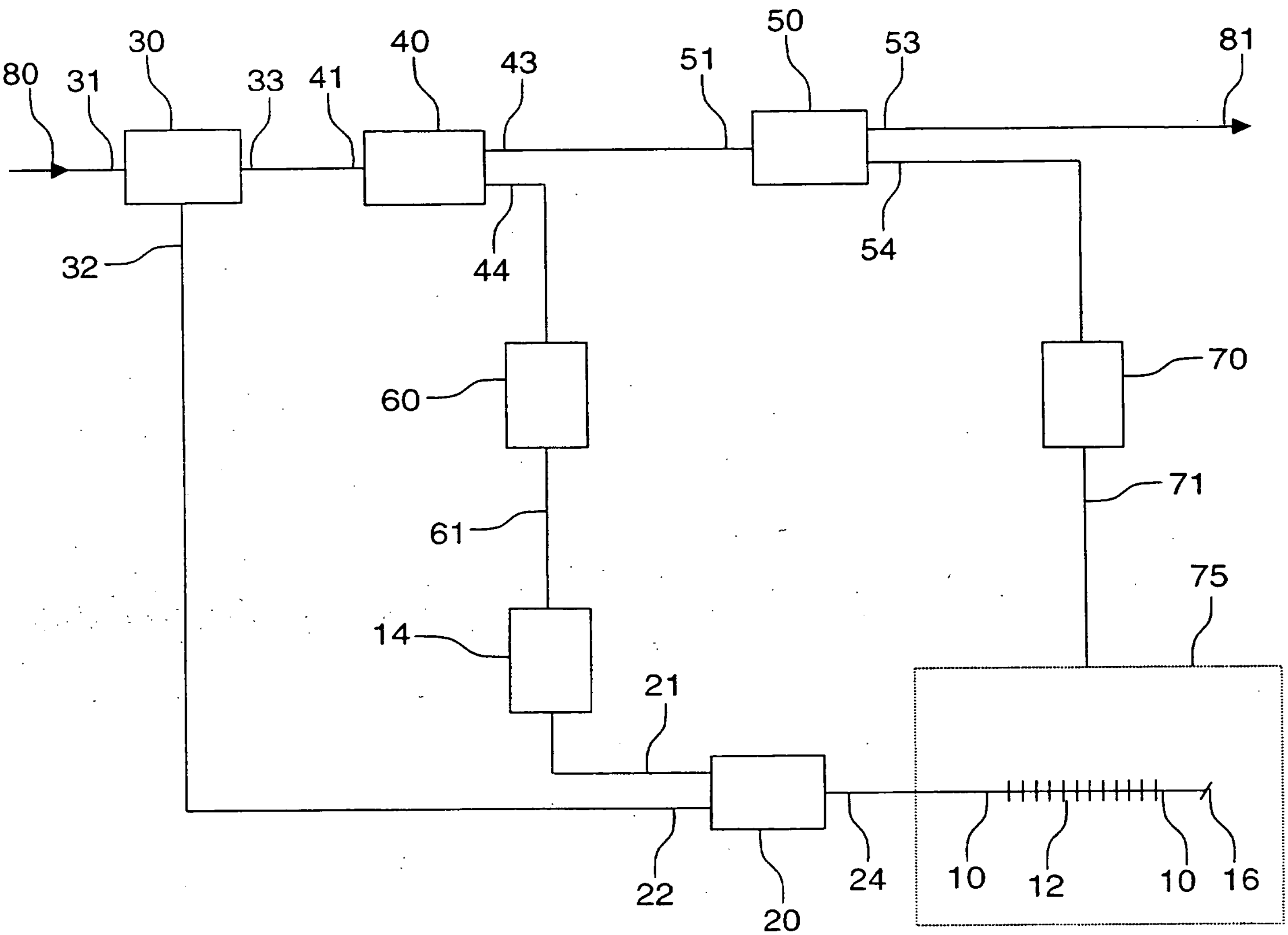
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FIG. 7